AN ATTEMPT (AND FAILURE) TO CORRELATE DUFF REMOVAL AND SLASH FIRE HEAT

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ABSTRACT

A detailed analysis is made of field data taken during a program of experimental broadcast burning of logging slash in northwestern Montana. An unsuccessful attempt was made to relate the amount of F and H layer duff burned out to the quantity of heat released by the slash burning, as estimated by theory. Inadequacies in the data and pitfalls of procedure are indicated in hopes of assisting experiment design in future work of this nature.

BACKGROUND

From the spring of 1967 to the fall of 1969, approximately 1,000 acres of Douglas-fir, larch, spruce, and fir logging slash were broadcast burned experimentally in two National Forest areas of western Montana--Miller Creek, northwest of Kalispell, and Newman Ridge, west of Superior. Forty-six research plots of 2-1/2 acres each were established within the fires at Miller Creek (Flathead National Forest) and twenty-seven 3-acre plots at Newman Ridge (Lolo National Forest). The research plots were extensively inventoried and instrumented to quantify various aspects of fuel loading, environmental conditions, and fire effects.

One of the significant statistical findings[1] of the research effort was a strong correlation between the reduction in duff depth and (1) upper duff moisture content and (2) Buildup Index. Because the heat load (Btu/ft^2 of surface) delivered to the site, as measured by water-can analogs (George 1969) was also found to be strongly correlated to these two parameters, it was natural to speculate that the heat load on the site played a causal role in duff removal.[1]

Duff depth reduction or removal is often an objective of prescribed burning because regrowth may be influenced by exposure of soil to seed. To help in formulating burning prescriptions, an effort was made to develop a relationship between heat released per unit area by burning of the slash fuels and the reduction in depth of duff observed on the site. The effort failed. The purpose of this report is to summarize this unsuccessful attempt in the hope that future research will profit from an understanding of the pitfalls encountered.

A theory was developed that relates the heat flux onto the surface of the duff layer to the amount of duff removed (depth reduction), using the duff weight loading and moisture profile as parameters.

Attempts were made to calculate the heat released by slash burning on the various sites. Using the fuel loadings by size class and species, Rothermel's (1972) fire spread model was exercised to obtain heat release rates. Another theory was developed[2] to try to predict the amount of large fuel that would be burned out in a slash-type fuel complex and so predict the heat released.

To apply these theories required an intensive review of the study data. For example, the greatest quantity of potential heat release in logging slash resides in the heavier fuels. A small error in the estimate of the loading of large pieces can exceed the total heat release potential of all the fine fuels. So, a review of measurement and data-reduction procedures was also required.

In the following sections, the measurement and data-reduction methods are briefly reviewed and accuracy of data is assessed. The theories are presented later, and the unsuccessful comparisons of predictions and measurements follow.

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[1]William R. Beaufait, Charles E. Hardy, and William C. Fischer. Broadcast burning in larch-fir clearcuts: the Miller Creek-Newman Ridge study. USDA For. Serv. Res. Pap. INT-___(in preparation).

[2]Frank A. Albini. Computer-based models of wildland fire behavior: a users' manual. USDA For. Serv. Gen. Tech. Rep. INT-___(in preparation).

DUFF DEPTH DETERMINATION

Two methods were used to determine duff depth reduction: (1) Direct measurement at three spots near each of 66 sample points, before and after the burn; (2) installation of 8-inch spikes, driven into the soil so that the head of the spike was at the upper duff surface prior to the fire, with measurement of the exposed spike length after the fire. Seventy-two spikes per plot were emplaced. The sixty-six 1-meter-long transects were the points at which the direct depth measurements were made, and because preburn and postburn transect locations were not necessarily the same, considerable internal variability was noted in that data. So the spike measurements were preferred for analysis of duff reduction.[3]

Measurements were recorded to the nearest centimeter, so an average duff depth before and after the burn was available, probably accurate to within 0.5 centimeter or less; these data should adequately represent average duff depth on the site, although the sample standard deviation was a large fraction of the mean in some cases (spot checked).

FUEL LOAD DETERMINATION

Fuel load was determined by size class, using the line transect method (Beaufait and others 1974), with sixty-six 1-meter transects the standard number per 2-1/2-acre plot. Inventories were taken before and after each plot was burned. Woody intercepts by species and size class (diameter <1 cm, 1-10 cm, >10 cm) were recorded and the diameters of the intercepted pieces of diameter greater than 10 cm were recorded. The data were reduced to histogram format for the larger sizes; that is, the weight loading was computed for diameters of 10 to 20, 20 to 30, 30 to 40 cm, and so on.

These data were inadequate to establish accurately the loadings of the larger size classes.

The reduction of data taken by the line-intercept method rests on the plausible assumption that the fuel pieces are horizontal, randomly oriented, and randomly scattered

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[3]William R. Beaufait, and others, op. cit.

on the ground. Such a distribution of pieces leads to a formula for the expected number of centerline intercepts per unit length of transect of the form

$$N' = (2/\pi)(\nu L) \tag{1}$$

where

N' = expected number of intercepts per unit transect length

ν = average number of fuel pieces per unit area of plot

L = length of fuel pieces.

This formula is valid whether the transect is one long, continuous transect or is composed of many short, randomly placed transects, so long as the fuels are randomly distributed.[4] The average weight loading for the size class in question is simply

$$W = \nu\rho(\pi D^2/4)L = \rho(\pi^2 D^2/8)N' \tag{2}$$

where

W = average weight loading of size class D (e.g., lb/ft^2)

ρ = weight density of fuel

D = diameter of fuel pieces.

The difficulty with the data in question arises from the fact that the observed variable, N', is Poisson distributed (Beaufait and others 1974), so a great deal of variability is to be expected.

The statistical problem here can best be posed in terms of the total number of intercepts (of a given size class) achieved in sampling the plot. Let the number be J. If the number of such intercepts *to be expected* is I, then the probability distribution for the sample outcome, J, is

$$P_I(J) = (I^J/J!)\exp(-I) \tag{3}$$

Table 1 is a brief tabulation of this distribution, and the summary at the bottom reveals the problem inherent in dealing with small numbers of intercepts. Note that in all cases shown, the probability of an error of at least 50 percent is high.

For the preburn and postburn inventories taken at Miller Creek, the average number of intercepts per meter of transect for the larger fuel sizes was as shown in table 2. Also shown is the average number of intercepts for a 66-meter total transect length.

[4]If the fuel elements are all alined in one direction (lying along the fall line), a small correction factor is required, assuming the transects are randomly oriented. The variance increases slightly with respect to the mean in that case.

Table 1.--*Probability of achieving J intercepts when I are to be expected and error introduced when J interpreted to represent the value of I*

Number of Intercepts achieved, *J*		Expected number of intercepts, *I*				
		1	2	3	4	5
0	Probability	0.368	0.135	0.050	0.018	0.007
	Error (percent)	(-100)	(-100)	(-100)	(-100)	(-100)
1		0.368	0.271	0.149	0.073	0.034
		0	(-50)	(-67)	(-75)	(-80)
2		.184	.271	.224	.147	.084
		(+100)	0	(-33)	(-50)	(-60)
3		.061	.180	.224	.195	.140
		(+200)	(+50)	0	(-25)	(-40)
4		.015	.090	.168	.195	.175
		(+300)	(+100)	(+33)	0	(-20)
5		.003	.036	.101	.156	.175
		(+400)	(+150)	(+67)	(+25)	0
6		.001	.012	.050	.104	.146
		(+500)	(+200)	(+100)	(+50)	(+20)
7		--	.003	.022	.060	.104
			(+250)	(+133)	(+75)	(+40)
8		--	.001	.008	.030	.065
			(+300)	(+167)	(+100)	(+60)
9		--	--	.003	.013	.036
				(+200)	(+125)	(+80)
10		--	--	.001	.005	.018
				(+233)	(+150)	(+100)
Probability that error is zero:		.368	.271	.224	.195	.175
Probability that error is at least 50 percent:		.632	.729	.384	.450	.260

Table 2.--*Average number of fuel intercepts by transect for Miller Creek prescribed burns*

	Fuel diameter (cm)			
	1-10	10-20	20-30	30-40
		INTERCEPTS PER METER		
Preburn	6.74	0.498	0.293	0.067
Postburn	1.85	.340	.171	.040
		INTERCEPTS IN 66 METERS		
Preburn	444.80	32.900	19.300	4.400
Postburn	122.10	22.400	11.300	2.600

The implication of these numbers in terms of the accuracy of weight loading estimation is shown in figure 1. In constructing figure 1, we have used the approximation that the estimate of the mean surface density is a statistic with Gaussian distribution (unbiased). Figure 1 is interpreted as follows: The ordinate is the tolerance, expressed as a percentage, in the estimation of the loading of any fuel size class. The "confidence level" is the probability that the sample estimate of the loading will fall within the tolerance band of the true value. The abscissa then gives the expected number of intercepts that must be achieved to obtain that confidence level and tolerance. For example, to be correct 95 percent of the time in asserting that the estimated loading is within ±30 percent of the true value, the expected number of intercepts must be 42. At that number of expected intercepts, the estimated loading will be within ±25 percent of the true value 90 percent of the time, within ±16 percent for 70 percent of the time, and within ±10 percent for 50 percent of the time.

The statistical design of the sampling procedure (Beaufait and others 1974) emphasized the taking of data for the fine fuels, and represents a sophisticated yet practical approach to that problem. The accuracy of the fine fuel loadings was generally very good. But, the accuracy of the estimates of weight loading by large size classes in the plots burned was generally poor. In fact, in nearly half the plots the postburn inventories showed higher loadings of large fuels (≥20 cm) than the preburn inventories. This is to be expected given the magnitude of errors anticipated in dealing with small samples.

Five plots in the Miller Creek series were sampled (preburn only) much more extensively than all the others. On units 111, 207, 308, 401, and 405 there were 231 1-meter transects. The improvement in large fuel loading estimation accuracy is substantial for these units. More data on these plots are presented later.

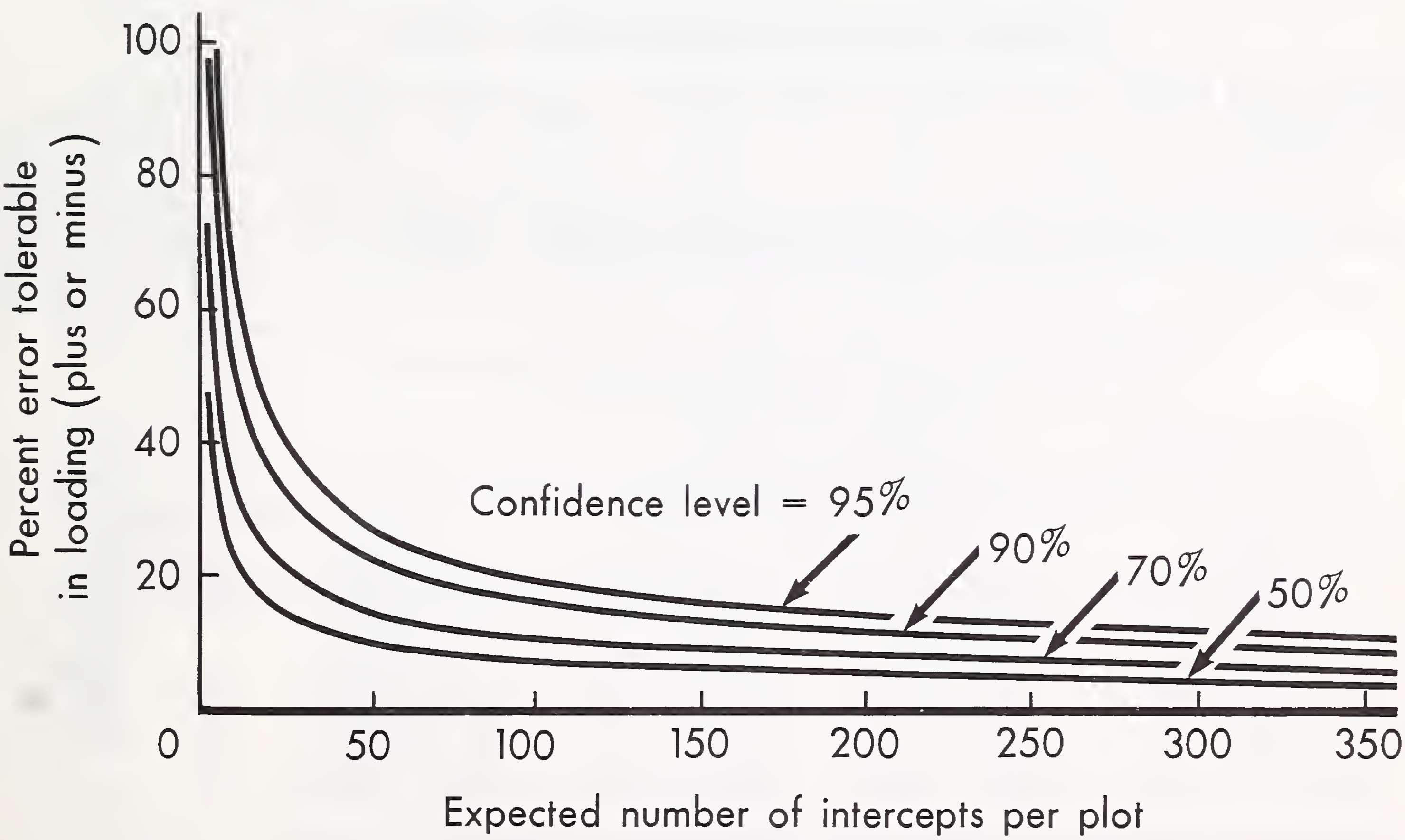

Figure 1.--Confidence level and error in estimating the loading by fuel size class on Miller Creek and Newman Ridge slash burn plots.

DUFF MOISTURE MEASUREMENTS

The critical role of duff moisture in influencing the amount of duff burned out has long been recognized. Duff moisture was measured in each of the plots in the Miller Creek/Newman Ridge series just prior to burning. Three points were sampled in each plot. The measurements were made for upper and lower duff mantle strata at each point.

Had these measurements indicated uniformity of duff moisture over the plot area, three samples for estimating mean upper and lower duff moisture content would probably have been adequate. That such was not the case is reflected in table 3, which shows the upper and lower duff moisture contents for the three sample points on the five intensively inventoried plots. Note that only in units 401 and 405 did the trend of moisture content with depth maintain the same mathematical sense for the three samples. At 11 of the 15 points, the duff moisture increased with depth, and at 4 it decreased. The author cannot explain why the mathematical sense should not have been uniform for each plot.

In unit 401, the lower duff moisture exceeded the range of the data format for two of the points, so are not accurately known.

Because these are small-sample statistics, conclusions must be drawn with great caution. But the sample standard deviations are so large compared to the mean values that clearly we are dealing with a locally variable quantity and should not infer a single moisture value (or profile) as representative of the entire unit. Table 3 shows the sample standard deviations. Only unit 405 seems "well behaved" with respect to these data.

In future field measurement efforts, causally related variables that exhibit such variability must be sampled in juxtaposition and treated as ordered sets of data.

Table 3.--*Upper and lower duff moisture content (percent) for the three sample points taken on units intensively inventoried for fuel loading, Miller Creek slash burns*

Unit No. (aspect)	Percent duff moisture content									
	Point 1		Point 2		Point 3		Average		Standard deviation	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
111 (N)	41	10	33	56	27	88	33.7	51.3	7.0	39.2
207 (E)	24	46	38	47	81	68	47.7	53.7	29.7	12.4
308 (S)	21	46	12	6	95	31	42.7	27.7	45.5	20.2
401 (W)	70	*	23	*	47	83	46.7	≥93.7	23.5	**
405 (W)	21	66	23	58	28	43	24.0	55.7	3.6	11.7

* Moisture content exceeded 99 percent, recorded as 99.
** Cannot estimate accurately.

DUFF WEIGHT LOADING

The weight loading of the duff mantle (F and H layers combined) was inferred from a correlation function relating depth of duff and weight loading (Beaufait and others 1974). These regressions were developed using 25 samples each from various plots of each slope exposure. The regression equations developed[5] are in terms of the dry weight of duff in a 5-inch-diameter cylinder as a function of the depth in millimeters. They are, for the various exposures:

$$\text{(NORTH)}\quad W = -10.412 + 1.298D \tag{4}$$

$$\text{(EAST)}\quad W = 15.331 + 1.372D \tag{5}$$

$$\text{(SOUTH)}\quad W = -16.055 + 1.559D \tag{6}$$

$$\text{(WEST)}\quad W = -5.415 + 1.369D \tag{7}$$

Because the equations and the data to which they were fitted agree so well, the representation of duff weight load from the average depth over the plot is probably adequate.

Slash Fuel Characteristics and Duff Loading on Five Units

The intercept-count data for the five Miller Creek units were reduced to estimates of loading by size class, using the site-specific relative frequency distributions of tree species and the foliage-weight/twig-weight ratio for each species. These data are available in tabular form from the author on request. The list of fuels on each plot included 40 to 50 entries. The total dry weight fuel loading, average duff depth and loading before burning, and the average duff depth after burning for the five intensively inventoried plots are shown in table 4. Derived quantities, such as fuel

Table 4.--*Fuel and duff loadings on five units, Miller Creek*

Unit No.	Dry slash load	Average duff depth		Preburn average duff load
		Preburn	Postburn	
	Lb/ft²	----------*cm*----------		*Lb/ft²*
111	6.60	4.21	1.11	0.714
207	5.35	3.01	0.56	.914
308	6.26	3.18	.50	.688
401	5.81	3.35	1.35	.584
405	4.56	4.29	.44	.820

[5]Rodney A. Norum. Unpublished data compiled in support of "Broadcast Burning in Larch-Fir Clearcuts: the Miller Creek-Newman Ridge Study," by Beaufait, Hardy, and Fischer. Data on file at the Northern Forest Fire Laboratory, Missoula, Montana.

loadings, heat release, etc., are given in British units for consistency with most American forestry literature. Data transcribed from the study material are left in the metric form in which they were recorded to facilitate comparison with the unpublished source data.

In terms of slash fuel loadings, there is little disparity among units in table 4, but in terms of load distribution by size class (table 5), the differences are considerable. The differences can be largely attributed to species variations on the sites. Unit 111 was predominantly fir and spruce; 207, fir and Douglas-fir/larch; 308 and 405, Douglas-fir and larch; and 401, fir with a mixture of Douglas-fir, larch, spruce, and yew. The other major fire-influencing parameters are wind, slope, fuel bed depth, and fuel moisture. These parameters are tabulated in table 6 for comparison.

The data presented in table 6, including the breakdown of loading by size class and species, and species-dependent fuel properties, were used in Rothermel's (1972) fire spread model to obtain fire spread characteristics. The data were also used in the theory that attempts to predict the amount of large fuel which will be burned and the heat released on the site.[6]

Although it was possible to compare the large-fuel-burnout theory with carefully inventoried slash burns in Canada (Stocks and Walker 1972), it was not possible to test the duff-burnout theory against independent data. The duff-burnout theory is briefly described below.

Table 5.--*Total slash loading by size class on five units, Miller Creek*

Unit No.	Size class (diameter in cm)						
	Foliage	0 - 1	1 - 10	10 - 20	20 - 30	30 - 40	40 - 50
	Dry loading (Lb/ft^2)						
111	0.1135	0.0923	0.3509	1.2842	2.7815	1.7143	0.2648
207	.0828	.0733	.7456	1.0598	2.1217	.6924	.5723
308	.0388	.0447	.5494	1.2585	3.0565	.9174	.3032
401	.1075	.0950	.7699	.7991	1.4754	1.5072	1.0539
405	.0458	.0561	.5174	1.3825	1.9667	.6625	0

Table 6.--*Fire-influencing parameters on five units, Miller Creek*

Unit No.	Fuel moisture			Slope	Estimated wind (20 ft)	Average depth
	Needles	0 - 1 cm	1 - 10 cm			
	- - - - - - *Percent* - - - - - -			*Percent*	*Mi/h*	*Ft*
111	5.1	7.5	25.5	20	12.7	2.69
207	17.1	16.8	27.8	60	6.6	2.76
308	21.6	19.2	22.2	10	8.9	2.22
401	7.7	12.5	19.5	10	9.1	3.06
405	4.5	6.5	18.3	10	18.3	2.16

[6]Frank A. Albini, op. cit.

DUFF-BURNOUT THEORY

The basic tenets of the theory proposed here for duff burnout under the influence of an external heat load on the surface of the duff mantle are:

1. If moisture content is less than some critical value, M_x, duff will burn with no external heat input.

2. The external heat load is applied slowly enough that the burnout of duff being dried by the external heat source keeps pace with the drying. As the external heat source dries the upper surface of the duff to moisture M_x, the surface layer burns. The external energy input is required only to dry the duff to moisture M_x.

3. The burning of the surface of the duff does not dry out the duff below the surface significantly, but supplies the heat needed to completely desiccate and ignite only successive infinitesimal surface layers.

4. The duff mantle is of uniform bulk density (based on dry weight).

5. The profile of moisture with depth is exponential in form.

This last assumption is clearly arbitrary. The other assumptions can be defended on heuristic or anecdotal evidence, but not on experimental data of which the author is aware.

The equations relating the heat load imposed on the duff surface (Q) to the amount of duff burned out depend upon the value of the initial surface duff moisture (M_s) and the duff moisture at the soil-duff interface (M_o) as well as the critical moisture content (M_x) for burning. This can easily be seen by considering the various logical possibilities:

1. <u>Surface moisture less than bottom moisture</u> ($M_s \leq M_o$)

   a. $M_o \leq M_x$

      In this case, the entire duff mantle would be burned without any added external heat load; $Q = 0$.

b. $M_s \leq M_x$, $M_o > M_x$

In this case, the upper duff would burn, without assistance from external drying heat, down to the point at which the moisture equals the critical value. Let this depth be X_1, and the initial duff depth be D. Because we have assumed the moisture profile to be exponential, we can express these relationships in terms of the moisture-profile parameter, α:

$$M_o \exp(\alpha D) = M_s \tag{8}$$

$$M_o \exp(\alpha X_1) = M_x \tag{9}$$

from which

$$X_1/D = 1 - \ln(M_s/M_x)/\ln(M_s/M_o) \tag{10}$$

Now the application of an external heat load, Q, could dry the remaining duff, starting at the upper surface (X_1) down to some final depth (X_F) from whatever moisture it was originally ($M_o \exp(\alpha X)$) to the critical value (M_x). If the bulk density of the duff is ρ_b, and the heat necessary to vaporize a unit mass of water is L, then the implicit heat balance is expressed by:

$$\int_{X_F}^{X_1} (M_o \exp(\alpha X) - M_x)\rho_b L dX = Q \tag{11}$$

Using equation (8) to eliminate the profile parameter, α, and equation (10) to eliminate X_1, equation (11) can be written as:

$$Q/\rho_b DLM_x = (1 - \frac{M_s}{M_x}\left(\frac{M_s}{M_o}\right)^{(X_F/D - 1)})/\ln\left(\frac{M_s}{M_o}\right) - (1 - \frac{X_F}{D} - \ln\left(\frac{M_s}{M_x}\right)/\ln\left(\frac{M_s}{M_o}\right)) \tag{12}$$

Here we use the dimensionless group $Q/\rho_b DLM_x$ to gage the external heat required. To calculate the heat input per unit area, Q, required to burn off the fraction $(1 - X_F/D)$ of the duff load, we must multiply the dimensionless parameter by the product of the duff loading ($\rho_b D$) and the latent heat parameter (LM_x).

c. $M_s > M_x$

In this case, external drying heat is required before even the surface will burn. Expressing the same heat balance as represented by equation (11) we have:

$$\int_{X_F}^{D} (M_o \exp(\alpha X) - M_x)\rho_b L dX = Q \tag{13}$$

which is simply expressed as:

$$Q/\rho_b DLM_x = \left(\frac{M_s}{M_x}\right) (1 - \left(\frac{M_s}{M_o}\right)^{(X_F/D - 1)})/\ln\left(\frac{M_s}{M_o}\right) - (1 - \frac{X_F}{D}) \tag{14}$$

2. <u>Surface moisture greater than bottom moisture</u> ($M_s \geq M_o$)

a. $M_s \leq M_x$

Here the entire duff mantle would burn out without additional external heat; $Q = 0$.

b. $M_s > M_x$, $M_o < M_x$

Here the upper surface would not burn without the addition of external drying heat, but if sufficient heat were added to burn the duff down to the point at which the moisture equals the critical value, the duff would burn all the way to the soil surface without any additional external heat. So there is a "break point" at depth X_2, where

$$X_2/D = 1 - \ln(M_s/M_x)/\ln(M_s/M_o) \tag{15}$$

which is formally the same as equation (11). For depths of burnout that do not reach X_2, the necessary heat balance is given by equation (13), which leads to equation (14).

For depths of burn that reach the level X_2, the heat input required is obtained by using $X_F = X_2$ in equation (14), which reduces to:

$$Q/\rho_b DLM_x = \left(\frac{M_s}{M_x}\right)\left(1 - \left(\frac{M_o}{M_s}\right)^{\ln(M_s/M_x)/\ln(M_s/M_o)}\right)/\ln\left(\frac{M_s}{M_o}\right) + \ln\left(\frac{M_s}{M_x}\right)/\ln\left(\frac{M_s}{M_o}\right) \tag{16}$$

c. $M_o \geq M_x$

In this case, the duff will burn only with the addition of external heat, and the heat balance relationship leads once again to equation (14).

The equations given just above were programed for the Hewlett-Packard 9820 calculator for calculation of $Q/\rho_b DLM_x$ as a function of $(1 - X_F/D)$, the fractional reduction in duff depth. In order to interpret the relationships that can be calculated, however, we must establish either:

1. one duff moisture profile representative of each unit; or

2. the fractions of total unit area that are represented by the three measured moisture profiles for each unit.

From the data presented in table 3, the first alternative is clearly untenable. The data simply will not support any such inference. The second alternative is also unattractive because one can do no better than to assign to one-third of each unit one of the three profiles sampled on that unit. Although such an assumption is consistent with the data, it is not verifiable. Nevertheless, in the absence of better data, the latter approach was taken.

Table 7.--*Computed values of heat load necessary to produce observed levels of duff depth reduction on five Miller Creek units*

Unit No.	Observed average duff depth reduction	Preburn duff load $\rho_b D$	Duff load remaining	Duff load reduction	Computed value of $Q/\rho_b DLM_x$ M_x=0.3	M_x=0.4	M_x=0.5	M_x=0.6
	Fraction	*Lb/ft²*			*Dimensionless*			
111	0.736	0.714	0.188	0.526	0.180	0.025	0.000	0.000
207	.814	.914	.170	.744	.705	.423	.235	.134
308	.843	.688	.108	.580	.730	.420	.230	.111
401	.597	.584	.235	.349	.495	.246	.105	.034
405	.897	.820	.084	.736	.182	.037	.000	.000

Because the equations relating heat load and duff depth reduction yield the parameter $Q/\rho_b DLM_x$ directly, it was necessary to compute the fractional duff depth reduction for each plot, for a given level of heat load, by "cross plotting" the direct relationships. That is, for each value of $Q/\rho_b DLM_x$ the average value of $(1 - X_F/D)$ was determined by interpolating that value for each of the three moisture profiles for each unit and averaging the results to obtain an estimator for the average value of $(1 - X_F/D)$ for the unit, were it subjected to the given heat load.

To further complicate the problem, the resulting curves are functions of the assumed value of M_x. For that reason, table 7 shows several entries for the normalized heat load ($Q/\rho_b DLM_x$) required to produce the observed fractional duff depth reduction. Also shown in table 7 are the duff weight loadings ($\rho_b D$) for the five units. For the purpose of these calculations, the unknown lower duff moistures on unit 401 were assumed to be 100 percent.

HEAT LOAD ON THE SITE AND DUFF REMOVAL

Using the data presented in table 7, one can estimate the heat load required to produce the observed amount of duff depth reduction.

The heat load on each site was investigated through the use of water-can analogs (George 1969; and footnote 1). These data can be compared to the heat loads calculated from the duff burnout measurements. Water-can weight losses are summarized in table 8. Assuming the average water-can weight loss on each site to be proportional to the heat load on that site, we can pick a standard site and normalize the data to obtain a relative measure of heat load. For this we use "standard unit" number 405, which had the highest water-can weight loss. The relative heat loads calculated (normalized to unit

Table 8.--*Summary of water-can weight loss data for five intensively inventoried Miller Creek Units. Initial weight of water for all measurements is 3,400 grams*

Unit No.	Number of reliable measurements	Average remaining water	Average water loss	Standard deviation
		- - - - - - - - - -	*Grams*	- - - - - - - - - -
111	35	2,212	1,188	465
207	36	2,672	728	368
308	33	2,616	784	408
401	35	2,601	799	371
405	33	1,790	1,610	365

207 [table 7]) are compared to the relative water-can losses on a scatter diagram (fig. 2). Figure 2 also compares the relative heat loads calculated (table 7) and the relative reaction intensities computed using the Rothermel spread model.

In all cases, calculated heat loads do not agree with the other measures of heat output. The scatter diagrams of figure 2 show that the calculated heat load requirements do not agree with water-can weight losses. There is better agreement between the reaction intensity trend and the water-can weight loss trend than between either trend and calculated heat load. Table 9 shows the water-can weight loss-versus-reaction intensity trend. Also shown in table 9 is a calculated value of the heat released based on the theory of burnout of the larger fuel elements and the average duff depth loss data taken from table 4.

It is not surprising that Rothermel's reaction intensity does not agree well with data for either duff removal or water-can loss because the reaction intensity, computed for a spreading fire, represents principally the rate of combustion of the fine fuels that propagate the flame front. In slash burns, the greatest part of the heat load is contributed by larger fuel elements that are strongly discounted by the spread model algorithm.

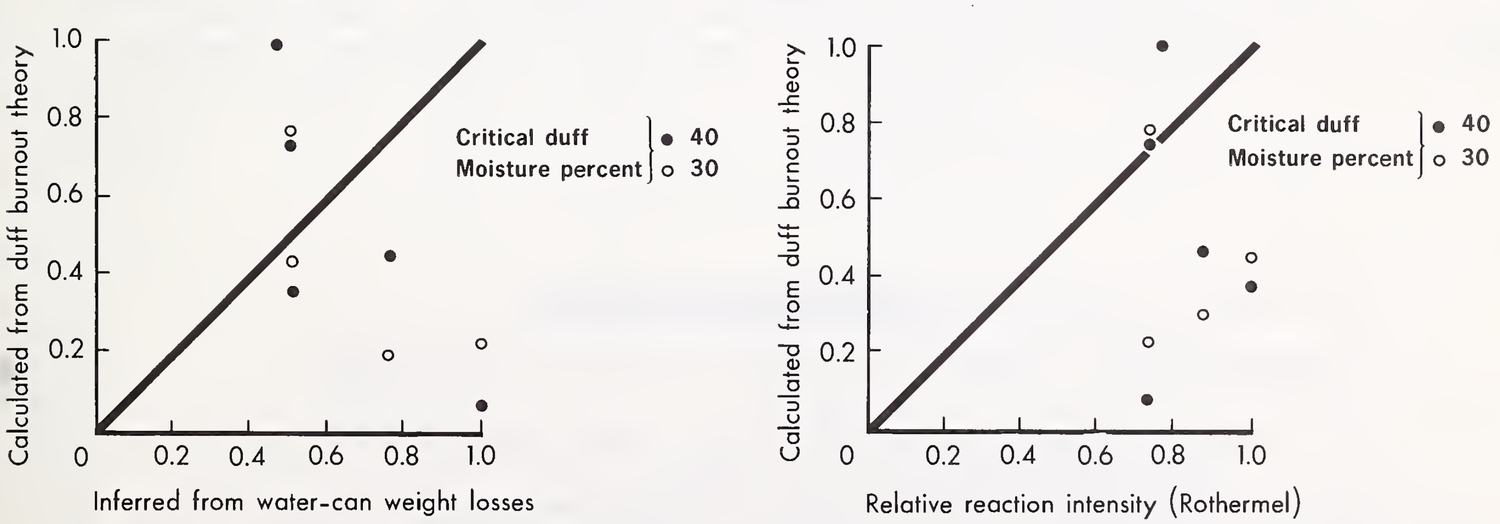

Figure 2.--Comparison of relative heat loads on five Miller Creek units, as determined from water-can weight loss data (upper) and reaction intensity (lower) and from duff-burnout theory.

Table 9.--*Heat load measures and duff burnout for five intensively inventoried Miller Creek units*

	Unit number				
	111	207	308	401	405
Average duff depth loss, cm	3.10	2.45	2.68	2.00	3.85
Average water-can weight loss, g	1,188	728	785	799	1,610
Rothermel's reaction intensity, $Btu/ft^2/min$	3,197	2,809	2,699	3,658	2,670
Computed total heat load from slash burnout (theory), Btu/ft^2	31,900	21,800	27,000	24,000	17,300
Computed relative heat load by slash burnout (theory)	1.00	.682	.845	.751	.541
Heat load required from duff-burnout theory, Btu/ft^2					
30 percent critical moisture	38.6	193.3	150.7	86.7	44.8
40 percent critical moisture	7.14	154.7	115.6	57.5	12.1
Computed relative heat load required (duff-burnout theory)					
30 percent critical moisture	.199	1.00	.779	.449	.232
40 percent critical moisture	.462	1.00	.747	.372	.0778

COMPARISON WITH VAN WAGNER'S FORMULA

For calculating duff consumed by fire under standing timber, Van Wagner (1972) proposed a formula that correlated well with the data for which it was generated. Supported by a simple theory, the equation is heuristically appealing. Rewritten in British units, his formula becomes:

$$W_D = 0.1926\ (1.418 - M)/(0.1774 + M) \tag{17}$$

where

W_D = dry weight loading of duff consumed, lb/ft^2

M = average moisture content of the duff (fraction of dry weight).

Applying this equation directly to the Miller Creek data poses two difficulties:

1. The equation predicts burning of duff under standing timber, where the duff mantle frequently represents a major part of the consumable fuel. On this basis, the equation should underestimate the amount of duff consumed when burned under a loading of logging slash.

2. The duff layer moisture, assumed to be uniform in Van Wagner's formula, is nonuniform (vertical and horizontal gradients exist) for the areas considered here.

Nevertheless, the formula provides a point of departure, and offers the possibility of establishing a lower limit for duff consumed. Calculations were based on three different "average moistures" per plot, and the average of three duff consumption predictions calculated. This was done because of the high variability of the moisture levels (table 3). Because the upper and lower duff moistures were frequently greatly different, an exponential vertical variation of moisture content was again assumed, so the mass-average moisture content at any point is given by:

$$\overline{M} = \frac{1}{D} \int_{0}^{D} M(x)dx = (M_s - M_o)/\ln(M_s/M_o) \tag{18}$$

Table 10 shows the values of the moisture contents so averaged, the predicted duff consumption values for each point, the average predicted duff consumption, and the observed values. As expected, the formula underestimated the degree of duff consumption in each case.

The results shown in table 10 indicate that the differences between the observed and predicted average values do not correlate at all with either Rothermel's reaction intensity or the predicted total heat load from slash burning (table 9). So, it is not possible to attribute "additional" duff burnout to these measures of external heat input.

Table 10.--*Comparison of duff consumption observed with that predicted by Van Wagner's formula for five Miller Creek slash burns*

Unit No.	Average moisture content (exponential vertical variation assumed): Point 1	Point 2	Point 3	Predicted duff consumption: Point 1	Point 2	Point 3	Average	Observed values
	- - - Percent - - -			- - - Lb/Ft^2 - - -				
111	22.0	43.5	51.6	0.581	0.309	0.251	0.380	0.526
207	33.8	42.3	74.3	.404	.319	.141	.288	.744
308	31.9	8.7	57.2	.426	.970	.217	.538	.580
401	84.1*	52.4*	63.3	.109	.245	.187	.180	.349
405	39.3	37.8	35.0	.346	.361	.390	.366	.736

* Lower duff moisture content assumed to be 100 percent.

DISCUSSION

Data presented in tables 9 and 10 support the following conclusions:

1. Calculations of the heat required to cause the amount of duff burnout observed do not correspond well with any of the measures of heat released (water-can weight loss, Rothermel's reaction intensity, or a theoretical estimate of slash burn heat release).

2. The average duff depth-loss does correlate well with the water-can weight loss.

3. Van Wagner's duff consumption formula underestimates the degree of duff burnout observed, as expected; but the degree of disagreement cannot be correlated to measures of slash fire heat release, either.

Factors that must be considered in evaluating these relationships (or lack thereof) include:

1. The theory used to predict the slash burn heat release is weak and has not been adequately tested.

2. The duff moisture data from which the required heat loads were calculated may be inadquate to provide a realistic appraisal of duff moisture content.

3. The theory behind the "required heat load" calculations is untested and may be inadequate.

4. The water-can weight loss may be generated by the burning of duff rather than by the burning of the slash fuel overburden. As such, it would represent only another means of estimating the duff load removal, not a measurement of heat released above the duff itself.

In summary, the analysis performed provided no additional theoretical relationships that might be useful in projecting the findings of these experiments to different situations. Gaps in the data prevented the confirmation or refutation of any of the theoretical relationships developed. The purpose of this report is to document these relationships and to capture the data. Perhaps future research can profit from the information presented here.

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1975. An attempt (and failure) to correlate duff removal and slash fire heat. USDA For. Serv. Gen. Tech. Rep. INT-24, 16 p. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

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- Logan, Utah (in cooperation with Utah State University)
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